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FINAL REPORT

EVALUATION OF ENERGY PRODUCTION POTENTIAL OF THE LINDEN LEE FARMS ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEM

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PREFACE

This report is intended to summarize the activities of a monitoring program conducted to determine an energy balance for the Linden Lee Farms' anaerobic digestion and electrical co-generation system operating on swine manure.

This report was prepared for government personnel, universities, industries, engineering firms, private research organizations and individuals attempting to design or evaluate anaerobic digestion technology applied to a swine operation.

ABSTRACT

The objective of the project was to determine a detailed energy balance for the anaerobic digestion and electrical co-generation system at Linden Lee Farms, a swine operation in Cornwall, Prince Edward Island.

An electrical generation system monitoring program was conducted to collect the data required to perform the energy balance. At a generator output of 2.5 kW or 6.3% of the rated capacity, only 5.6% of the energy supplied as fuel went into work energy. At an output of 15 kW or 37.5% of the rated capacity, 21.8% of the fuel energy went into work. At higher generator outputs a significantly greater percentage of the fuel energy is converted to work, whereas at lower outputs, most of the fuel energy goes into radiant heat. It is more fuel efficient, both for the production of electricity and recoverable heat energy, to run an engine generator at or near its maximum rated capacity, even if for only a short period of time rather than to run it continuously at lower loadings.

It was estimated that at the current size of Linden Lee Farms (225 sows farrow-to-finish), 137 m^3 biogas/day would be produced. At this rate of biogas production, the engine generator set could run for 9.5 hours and produce 15 kW.

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EXECUTIVE SUMMARY

In April 1983, Energy, Mines and Resources Canada (EMR) provided funding support through the Conservation of Renewable Energy Demonstration Program (CREDP) to construct and monitor a full-scale anaerobic digestion and electrical co-generation system at Linden Lee Farms in Cornwall, P.E.I.

During the initial monitoring program conducted at Linden Lee Farms, it was observed that the daily volatile solids production of 386 kg/d was only 67% of the value calculated with figures published by Agriculture Canada (1981). At another full-scale anaerobic digestion and electrical co-generation facility, Selves Farms Ltd., in Fullarton, Ontario, the daily volatile solids production of 313 kg/d was only 54% of the value calculated with the Agriculture Canada figures (CANVIRO, 1984). The volatile solids production figures are particularly important because they are used to calculate loading rates to an anaerobic digester and to calculate the size of digester and the energy production potential.

The specific biogas production figures observed at Linden Lee Farms during the monitoring program and figures observed at Selves Farms (CANVIRO, 1984) also varied considerably from figures reported by Agriculture Canada (1981).

The overall objective of this project was to evaluate the energy production potential for the Linden Lee Farms anaerobic digestion and electrical co-generation system by conducting a mass and energy evaluation on the Linden Lee system and then comparing this information to the Agriculture Canada published information and information collected at Selves Farms Ltd.

A detailed review of the manure production and manure characteristics information was performed and comparisons were made to Agriculture Canada published literature and to data collected at Selves Farms.

An energy balance around the co-generation system was performed and, at a generator output of 2.5 kW, 52.5% of the fuel consumed went into radiant heat, 24.0% into the exhaust gas, 17.9% into the water jacket, and 5.6% went into work. At an electrical output of 7.5 kW, 50.25% of the fuel consumed went into radiant heat, 19.4% into the exhaust gas, 17.2% into the water jacket, and 13.2% into work. At 10 kW output, 49.4% of the fuel went into radiant heat, 19.0% into the exhaust gas, 15.8% into the water jacket, and 15.8% into work. At 15 kW output, 46.5% of the fuel went into radiant heat, 21.8% into work, 18.5% into the exhaust gas, and 13.1% into the water jacket.

The estimated energy production potential for Linden Lee Farms was estimated, based on a production of 456 kg VS and a specific gas production rate of 0.3 m^3/kg VS.d, at 137 m^3 of biogas/d or 3034 Mj/d. This energy would fuel the existing co-generation system for 9.5 hr at an output of 15 kW. The biogas produced while the engine was shut down would have to be stored (approximately 83 m^3).

The report recommends operating the co-generation system at the maximum practical load to maximize the fuel efficiency and the heat recovery and, if economically feasible, installing biogas storage to store biogas when the engine is not running.

1.0 INTRODUCTION AND BACKGROUND

1.1 Introduction

During the past 30 years, both the size and intensity of farming operations in North America have increased. During the same period, the livestock industry has become more highly energy dependent through the extensive use of mechanized equipment operating on fossil fuels and electricity. While no shortage of energy is anticipated in Canada in the near future, recent and projected energy cost increases have made farm management more aware of the energy component of operating costs.

As Canadian farms increase in size and the rural-urban interface narrows, odour reduction and pollution control is also becoming an area of concern for many producers. The economic impact of pollution control on farming activities is difficult to determine. However, the regulation of farming activities and enforcement of environmental codes of practice will undoubtedly increase the cost of farm pollution control during the next decade.

Anaerobic digestion is one technology that has the potential to reduce the cost of energy on medium- to large-scale agricultural operations, while providing a significant reduction of environmental pollution (primarily odour) from farming activities.

The biogas (65% methane, 35% carbon dioxide) produced during anaerobic digestion of animal wastes has been used successfully to fuel boilers, grain dryers and electrical co-generation units. Electrical energy on today's medium- to large-scale swine production units represents the fourth largest cost exceeded only by feed, interest charges and labour cost. Electricity is used at a relatively constant rate year round in most swine operations. The winter heating requirements are replaced by higher summer ventilation requirements, keeping the electrical use relatively constant. A number of areas, farrowing rooms, and nurseries require space heating for most of the year, making the simultaneous production of electricity and recovered waste heat (co-generation) amenable to most swine operations.

Internal combustion reciprocating engines have proven to be very effective in co-generation applications. Approximately 30% to 35% of the heat energy available from the fuel burned in a reciprocating engine is converted to mechanical work. The remaining energy is available in the form of heat which must be recovered from the engine. In order to improve the cost efficiency of a co-generation system it is necessary to recover and use as much of this heat as possible.

The largest fractions of this heat are exhausted in the combustion gases or removed from the engine by a water jacket system. A small fraction of this heat is lost through radiation.

Most of the heat rejected to the water jacket and up to 70% of the heat rejected to the exhaust gas can be recovered and used for water or space heating or for other heating requirements.

1.2 Background

In April 1983, Energy, Mines and Resources (EMR) provided funding support through the Conservation of Renewable Energy Demonstration Program (CREDP), for a proposal prepared by CANVIRO to construct a full-scale anaerobic digestion and electrical co-generation system at Linden Lee Farms in Cornwall, P.E.I. EMR signed a contract with Linden Lee Farms to provide 66-2/3% funding of the capital costs of the system, and to fund the engineering and performance monitoring of the system. The results of the monitoring program are described in a report entitled "The Demonstration of Energy Production and Conservation by Anaerobic Digestion and Electrical Co-Generation of Swine Manure" (CANVIRO, 1985).

During the initial monitoring program conducted at Linden Lee Farms it was observed that the volatile solids productions of 386 kg/d was only 67% of the value calculated with figures published by Agriculture Canada (1981). At another full-scale anaerobic digestion and electrical co-generation facility, Selves Farms Ltd., in Fullarton, Ontario, the volatile solids production of 313 kg/d was only 54% of the value calculated with the Agriculture Canada figures (CANVIRO, 1984). The volatile solids production figures are particularly important because they are used to calculate loading rates to an anaerobic digester and to calculate the size of digester required for these loadings.

The specific biogas production figures observed at Linden Lee Farms during the monitoring program and figures observed at Selves Farms (CANVIRO, 1984) also varied considerably from figures reported by Agriculture Canada (1981).

The design of anaerobic digesters and the sizing of electrical co-generation system are critically dependent on accurate organic and volumetric data. Accurate data for different animal wastes must be developed to ensure the proper sizing of tanks, biogas storage and handling equipment, and biogas utilization equipment.

The overall objective of this project was to evaluate the energy production potential for the Linden Lee Farms anaerobic digestion and electrical co-generation system. The specific objectives of the project were as follows:

1. Conduct a system monitoring program to determine an energy balance for the Linden Lee Farms' anaerobic digestion and electrical co-generation system and compare the energy balance with figures supplied by the engine generator set supplier.

2. Compare the volatile solids production with respect to animal live weight at Linden Lee Farms' and compare it to the figures published by Agriculture Canada (1981) and to the figures observed at Selves Farms where the animals are fed a corn/soybean ration.

3. Determine the specific biogas production at Linden Lee Farms and compare it to the figures published by Agriculture Canada (1981) and to the figures observed at Selves Farms.

2.0 FACILITY DESCRIPTION

A schematic of the Linden Fee Farms anaerobic digestion and electrical co-generation system is shown in Figure 1. The system consists of a 6.6 meter diameter by 6.6 meter high, totally enclosed, circular reinforced concrete tank. The tank is insulated with 5 centimeters of urethane foam insulation covered with a UV barrier top coat. The digester contents are continuously mixed with two submersible style low-energy mixers, one located near the bottom of the digester running continuously, and the other one operating near the surface to break up any scum formation.

Manure from the finishing barn, starter barn and neighbouring poultry and swine farm is pumped once daily to the digestion tank using the manure transfer pump. The digested liquid overflows through a gas/liquid trap assembly located on the digester to a nearby storage tank and lagoon.

The biogas is withdrawn from the digestion tank and directed through a flame arrester, sediment trap, gas meter and gas blower to a 23 cubic meter low pressure biogas storage tank. The storage tank acts as a buffer between daily gas production and daily use.

The biogas is used, without scrubbing, to fuel a 55 kW natural gas engine and drive a 40 kW electrical generator. The electrical power is used to displace purchased power to the farm.

The heat from the engine cooling system and from an exhaust gas heat exchanger is recovered and used to heat the farm house, and the digestion system. Radiant heat from the engine is used to heat the workshop.

The relatively odour-free liquid remaining after anaerobic digestion flows by gravity to an earthen storage lagoon and is used as fertilizer on the farm land.

2.1 Digester Heat Exchanger

The digester heat exchange system consists of approximately 110 meters of 5 cm diameter low carbon steel pipe arranged in five loops, in series, approximately 0.2, 0.4, 0.6, and 1.0 meters off the bottom of the digestion tank, and approximately 0.5 meters from the digester exterior wall.

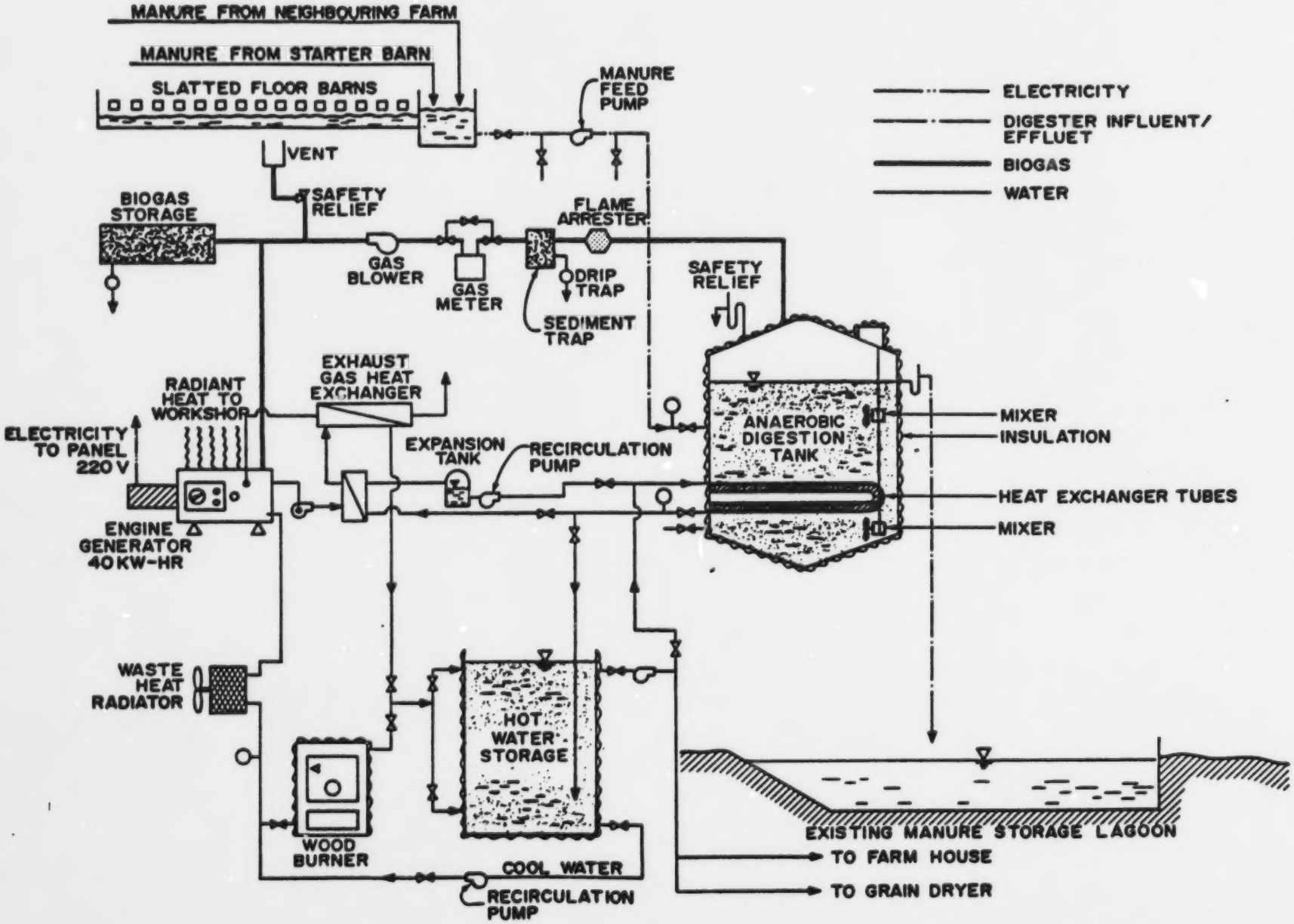


FIGURE 1 — SCHEMATIC OF THE LINDEN LEE FARMS ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEM

2.2 Digester Mixing System

The initial digester mixing system consisted of two submersible mixers. The mixers were single phase and this appears to have caused problems with starting and running the mixers for extended periods of time. In 1987 the two submersible mixers were replaced with a hydraulically-powered low-speed prop mixer.

2.3 Biogas Handling and Storage System

The gas handling system consists of a flame arrester, sediment/moisture trap, biogas flow meter and a rotary lobe biogas blower.

A 23 cubic meter steel biogas storage tank proved to be the most economical form of biogas storage. Several coats of rust-resistant paint were applied by hand to the exterior of the biogas storage tank for protection from corrosion. A condensate removal line was placed in the biogas storage tank. The tank is located behind the workshop near the engine generator set.

When the biogas storage tank is full (40 kPa), a pressure relief valve vents the excess gas to a vent stack mounted on the side of the digester control building. The vent extends 1 meter above the peak of the building roof.

2.4 Digester Control Building

A digester control building was constructed to house the gas handling and safety equipment. The digestion tank wall forms one wall of the building. All of the connections to the interior of the digester, with the exception of the biogas line, manure and effluent lines, are accessible through the building.

The building is approximately 2 m by 2 m and is of frame construction with coloured metal siding on a poured concrete foundation and a gravel floor. All of the piping, with the exception of the biogas lines, were brought into the building below grade.

2.5 Electrical Generation System

The electrical generation system consists of a 6 cyclinder natural gas fueled internal combustion engine, a 40 kW induction 220 V - single phase generator, an engine water jacket heat recovery system, and an engine exhaust gas heat recovery system.

The engine was designed to operate on both propane and biogas. It automatically switches from biogas to propane when the biogas pressure drops and automatically returns to biogas when the biogas pressure is restored.

The engine is equipped with a biogas pressure reduction valve to reduce the biogas pressure from the storage pressure of up to 40 kPa to the 3.5 kPa required by the low energy fuel carburetor.

The engine is equipped with two over-temperature shut downs, an over-speed and a low-oil-pressure shutdown.

The biogas and propane fuel supply lines automatically close if any of the shutdowns are tripped.

The electrical control system consists of a load sensing module, import/export module, and a reverse power relay module.

When the engine is started, the engine governor brings the engine to the synchronization speed of the generator and then maintains this speed until it is sychronized with the grid. When synchronization is achieved, the main contact relay closes and the induction generator field is excited and starts to produce power.

The import/export module controls the total power generated by the generator according to the following:

1) If the import module is set to zero, all power for the farm is generated by the generator up to its capacity. When the generator capacity is exceeded, the remaining required power is imported from the grid.

2) If the import module is not set to zero, then a percentage of the power required by the farm is imported (ie. if the import setting is at 50%, then 50% of the farm power will be supplied by the generator and 50% will be supplied by the grid).

3) If the export module is set to zero, no power will be exported to the grid.

4) If the export module is not set to zero, then a percentage of the generated power will be exported (ie. if the export setting is set at 20%, then the generator will export 20% of the power generated to the grid). If the farm demand exceeds the generator capacity then the exported power will be reduced as required.

The reverse power relay is provided as a safety feature. If the grid power is shut down, the reverse power relay will sense the loss of power and disconnect the engine generator from the grid until the power on the grid is returned. This protects anyone working on the power line from electrical shock in the event that the generator exports power.

The induction generator is also equipped with a capacitance bank. The capacitors provide a small reserve of power that can be used to excite the generator in the event that no excitation power is available when the grid power is off.

2.6 Heat Recovery System

The engine heat recovery system consists of two complete and separate cooling water circuits.

The primary engine cooling circuit consists of a water-to-water shell and tube heat exchanger, a coolant expansion tank, a recirculation pump and the digester heating coils.

The coolant in this circuit is pumped through the engine heat exchanger where it gains heat from the engine. The coolant flows to the coolant expansion tank to release any entrapped air and/or to expand as the coolant heats up. The suction side of the recirculation pump is connected to the bottom outlet of the expansion tank and the coolant is pumped through the digester heating coils and then returns to the engine heat exchanger. The flow rate through this loop regulates the temperature between 45°C and 55°C.

The engine operating temperature is regulated at 85°C by a thermostat located in the engine block.

A second heating loop consists of the engine recirculation pump, an exhaust manifold heat exchanger, an exhaust gas-to-water heat exchanger, a 27 m^3 hot water storage tank and a waste heat radiator.

The waste heat radiator is connected in the cool water return from the hot water storage tank. A temperature sensor turns on the waste heat radiator fan if the cool water return temperature exceeds 75°C.

The hot water storage tank is connected to the hot water heating system in the house and to a hot water radiator in the grain dryer. Hot water from this tank is circulated as required through the house and grain dryer.

3.0 SAMPLING AND MONITORING PROGRAM

A sampling and monitoring program was conducted at Linden Lee Farms to monitor the operation of the anaerobic digestion and electrical co-generation system. The program was divided into two parts. The first part consisted of a digestion system monitoring program and the second part consisted of an electrical generation system monitoring program.

3.1 Digestion System Monitoring Program

The digestion system monitoring program was conducted previously at Linden Lee Farms as part of a more extensive monitoring program (CANVIRO, 1985). The digestion system monitoring program consisted of the daily collection of digester influent and effluent samples and the maintenance of an operational log sheet. A record of the barn inventory was maintained during the study and a comparison to the manure production was made. During this period, manure from a neighbouring farm was being added to the manure from Linden Lee Farms in a holding tank before pumping it into the digester. A summary of the average barn inventory for Linden Lee Farms and the neighbouring farm during the study period is presented in Table 1.

Table 1
SUMMARY OF BARN INVENTORY

Animal	Number of Animals
Linden Lee Farms	
Sows & Boars	250
Pigs (1 day - market)	2000
Neighbouring Farm	
Sows & Boars	40
Pigs (1 day - market)	350
Laying Hens	1500

Digester influent samples were collected prior to the digester inlet and consisted of a combination of manure from the neighbouring farm and Linden Lee's finishing, farrowing and dry sow barns. Samples of digested effluent were collected

at the digester outlet. The daily samples were stored in a refrigerator and shipped to CANVIRO's analytical laboratory in Kitchener, Ontario once a week. The samples were analyzed for total solids (TS), total volatile solids (TVS), and weekly composite samples were analyzed for total Kjeldhal (TKN) and Ammonia Nitrogen (NH_3-N). A weekly sample of biogas was also collected and analyzed for gas quality. The results of the sampling program are summarized in Table 2.

Table 2
SUMMARY OF THE DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS

Parameter	Digester Influent		Digester Effluent		% Removal
	Mean	SD*	Mean	SD*	
pH	6.7	0.22	7.8	0.16	-
Total Solids (%)	3.53	1.14	2.36	0.47	33.1
Volatile Solids (%)	2.42	0.86	1.50	0.39	38.0
TKN (mg/L)	3816	627	3802	339	0.4
NH_3-N (mg/L)	2736	439	3133	290	-14.5

* Standard Deviation

During the digester monitoring program, an operational log sheet was maintained onsite to record the relevant operational information. The information collected daily included manure production, biogas production and digester loading data. A summary of the data collected is presented in Table 3.

Table 3
SUMMARY OF DIGESTER OPERATIONAL PARAMETERS

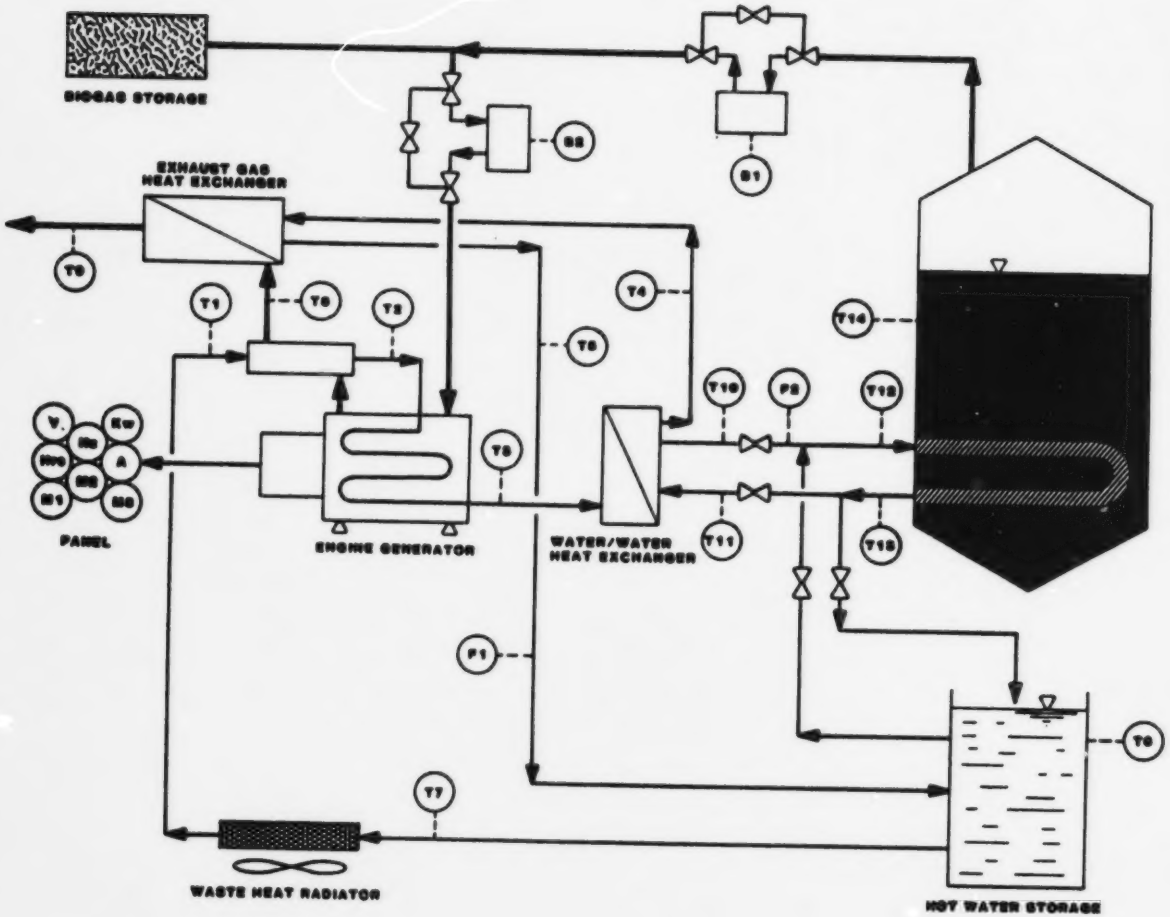
Parameter	Mean	SD*
Manure Volume Pumped (m^3/d)	16.18	3.47
Digester Loading (kg VS/d)	386	167
Digester Loading Rate (kg VS/m^3.d)	1.35	0.59
Hydraulic Retention Time (d)	18	-
Biogas Production (m^3/d)	135	63
Specific Biogas Production (m^3/kg VS.d)	0.30	0.15
Methane Content (%)	59.6	2.3

*Standard Deviation

3.2 Electrical Generation System Monitoring Program

An electrical generation system monitoring program was conducted to evaluate the performance of the system under a series of engine loadings. The locations of the temperature sensors, gas meters, flow meters, electrical meters and the electrical panel are shown in Figure 2. Fourteen temperature sensors were installed at the inlet and outlet of the heat exchangers, the engine water jacket, the digestion tank, and the hot water storage tank. Two flow meters were installed to measure the flow in the engine cooling loop and in the digester heating loop. Electric meters were installed to measure the total electricity generated, imported and exported. Readings of voltage, power, amperage, frequency, and hours of operation were recorded from the electrical panel.

During each trial run, the load on the generator was adjusted by either adding to or removing from the generator farm equipment that requires electrical power, such as feed grinding equipment, the farm house, etc. The generator was allowed to run for 30 minutes at each desired loading before any data was recorded. The temperature, flows and power were recorded four times during a 30 minute period for each trial run. The data collected during the electrical cogeneration system monitoring program was averaged for each period and used in the energy balance calculations. A summary of the data is presented in Appendix A.



SCHEMATIC LEGEND

TEMPERATURE SENSORS

- T1 - Cool water return.
- T2 - Engine block feed water.
- T3 - Water/water heat exchanger. Hot water.
- T4 - Water/water heat exchanger. Cool water.
- T5 - Water/exhaust gas heat exchanger. Hot water outlet.
- T6 - Hot water storage tank.
- T7 - Cool water return. Waste heat radiator inlet.
- T8 - Exhaust gas inlet.
- T9 - Exhaust gas outlet.
- T10 - Hot water to digester.
- T11 - Cool water from digester.
- T12 - Hot water inlet at digester.
- T13 - Cool water outlet at digester.
- T14 - Digester temperature.

BIOGAS METERS

- B1 - Biogas meter at digester.
- B2 - Biogas meter at engine gen. set.

FLOW METERS

- F1 - Engine cooling water loop.
- F2 - Digester heating loop.

ELECTRIC METERS

- M1 - Total electricity generated.
- M2 - Total electricity imported.
- M3 - Total electricity exported.

ELECTRIC PANEL

- V - Volts.
- Hz - Hertz.
- Kw - Kilowatts.
- Hrs - Hours of operation.
- A - Amps.

Figure 2
SCHEMATIC OF TEMPERATURE SENSOR, GAS METER & FLOW METER LOCATIONS AT LINDEN LEE FARMS ANAEROBIC DIGESTION & ELECTRICAL CO-GENERATION SYSTEM

4.0 RESULTS AND DISCUSSION

4.1 Digestion System

A comparison between the data collected at Linden Lee Farms, the data collected at Selves Farms Ltd., and the figures published by Agriculture Canada is presented in Table 4. The data presented in Table 4 has been prorated to a 2000-head growing and finishing operation to assist in the comparison.

Table 4
COMPARISON OF MANURE CHARACTERISTICS FOR A 2000-HEAD (120,000 kg LIVE WEIGHT) GROWING AND FINISHING SWINE OPERATIONS

Parameter	Agriculture Canada*	Selves Farms Ltd.**	Linden Lee Farms***
Manure Volume (L/d)	18200	14000	16200
Moisture Content (%)	91.0	95.9	96.5
Volatile Solids Content (%)	6.8	2.9	2.4
Volatile Solids Production (kg VS/d)	576	313	386
Specific Volatile Solids Production (kg VS/1000 kg live weight.d)	4.8	2.6	3.2
Energy Production Potential (GJ/d)	9.7	4.9	4.4
Biogas Production (m^3/kg VS fed.d)	0.5	0.7	0.3

References * Agriculture Canada (1981)
** CANVIRO (1984)
*** CANVIRO (1985)

The design of anaerobic digestion systems on agricultural wastes is usually based on a volatile solids loading rate and hydraulic retention time. The hydraulic loading information published by Agriculture Canada appears to be adequate. However, there are significant differences between the volatile solids production statistics published by Agriculture Canada and those observed at Selves Farms and Linden Lee Farms. At Linden Lee Farms, manure is also collected from a neighbouring swine and poultry operation. It was difficult to separate the volumes and concentrations of the manure from the various sources. This made the calculations

of loading rates difficult. The data collected at Selves Farms was collected over a longer period of time when accurate barn inventory statistics were being kept.

Based on the data from Linden Lee Farms and Selves Farms, the Agriculture Canada volatile solids production statistic appears to over-estimate the actual volatile solids produced by a factor of between 1.5 and 1.8. The swine ration at Selves Farms is predominantly corn and soybean, while the rations at Linden Lee are barley, wheat, rye and soybean based. This may account for some of the difference between the two farms. Generally, the digestibility of the corn-soybean ration is slightly higher than the grain-soybean (approximately 10%). The difference in digestibility may result in high volatile solids in the manure from the grain-soybean fed swine. This difference does not appear to be enough to account for the volatile solids difference between the collected data and the Agriculture Canada statistic.

A significant difference between the specific gas production rates at Linden Lee Farms and Selves Farms was observed. At Selves Farms the finishing animals are floor-fed whereas at Linden Lee Farms all pigs are fed from feeders. A higher percentage of feed may be wasted by the floor-feeding method, increasing the anaerobic digestibility of the manure and resulting in a higher specific biogas production rate.

Since the completion of the mass balance study (volatile solids production), Linden Lee Farms have expanded their herd to a 225-sow farrow-to-finish operation by the construction of a gestation, farrowing, nursery and grower barn.

Estimates of manure volumes and characteristics for Linden Lee Farms as it exists at the writing of this report are summarized in Table 5. The figures were estimated by determining the current animal live weight for the expanded operation and using the manure-volumes-per-animal statistics published by Agriculture Canada (1981) and the volatile solids production figures collected at Selves Farms during an extensive monitoring program.

Table 5
ESTIMATED MANURE CHARACTERISTICS FOR LINDEN LEE FARMS

Parameter	Mean Value
Manure Volume (m^3/d)	18.8
Specific Volatile Solids Production (kg VS/1000 kg live weight.d)	2.6
Volatile Solids Production (kg VS/d)	456

The anticipated manure volume for the expanded operation will be 18.8 m^3/d with the total volatile solids production estimated to be 456 kg/d.

4.2 Electrical Generation System

A digester system energy balance was performed with the data collected during the electrical generation system monitoring program. The results of the energy analysis are summarized in Table 6.

Table 6
ENERGY BALANCE FOR THE LINDEN LEE FARM ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEM

Parameter	Generator Output 2.5 kW	% of Fuel In	Generator Output 7.5 kW	% of Fuel In	Generator Output 10 kW	% of Fuel In	Generator Output 15 kW	% of Fuel In
Fuel Consumption (kJ/hr)	179,000	-	227,000	-	253,000	-	275,000	-
Water Jacket (kJ/hr)	32,000	17.9	39,000	17.2	40,000	15.8	36,000	13.1
Exhaust Gas (kJ/hr)	43,000	24.0	44,000	19.4	48,000	19.0	51,000	18.5
Radiant Heat (kJ/hr)	94,000	52.5	114,000	50.2	125,000	49.4	128,000	46.5
Work (kJ/hr)	10,000	5.6	30,000	13.2	40,000	15.8	60,000	21.8

The fuel consumption figures were obtained from engine performance curves provided by the engine supplier. The supplier curves are presented in terms of anticipated fuel consumption versus engine mechanical energy output. The mechanical energy output was converted to generator electrical output by dividing the measured generator output, as recorded during the program, by 0.9 (the electrical conversion efficiency of the electrical generator). The water jacket and exhaust gas figures were calculated from temperature differentials and water flow rates across each of the heat exchangers. The electrical energy output from the generator was converted to mechanical work and then to heat energy and presented in the table (ie. 2.5 kW-hr/0.9 efficiency x 1 W/J/S x 60 second/min x 60 min/hr).

The percentage of the fuel consumed that is translated into the water jacket, exhaust gas, and radiant heat all decreased as the generator output increased, while the percentage of fuel consumed that went into work increased. At a generator output of 2.5 kW, 52.5% of the fuel consumed went into radiant heat, 24.0% into the exhaust gas, 17.9% into the water jacket and 5.6% went into work.

At an electrical output of 7.5 kW, 50.2% of the fuel consumed went into radiant heat, 19.4% into the exhaust gas, 17.2% into the water jacket and 13.2% into work. At 10 kW output, 49.4% of the fuel went into radiant heat, 19.0% into the exhaust gas, 15.8% into the water jacket and 15.8% into work. At 15 kW output, 46.5% of the fuel went into radiant heat, 21.8% into work, 18.5% into the exhaust gas and 13.1% into the water jacket. A summary of energy balances at the various electrical outputs tested is illustrated in Figure 3.

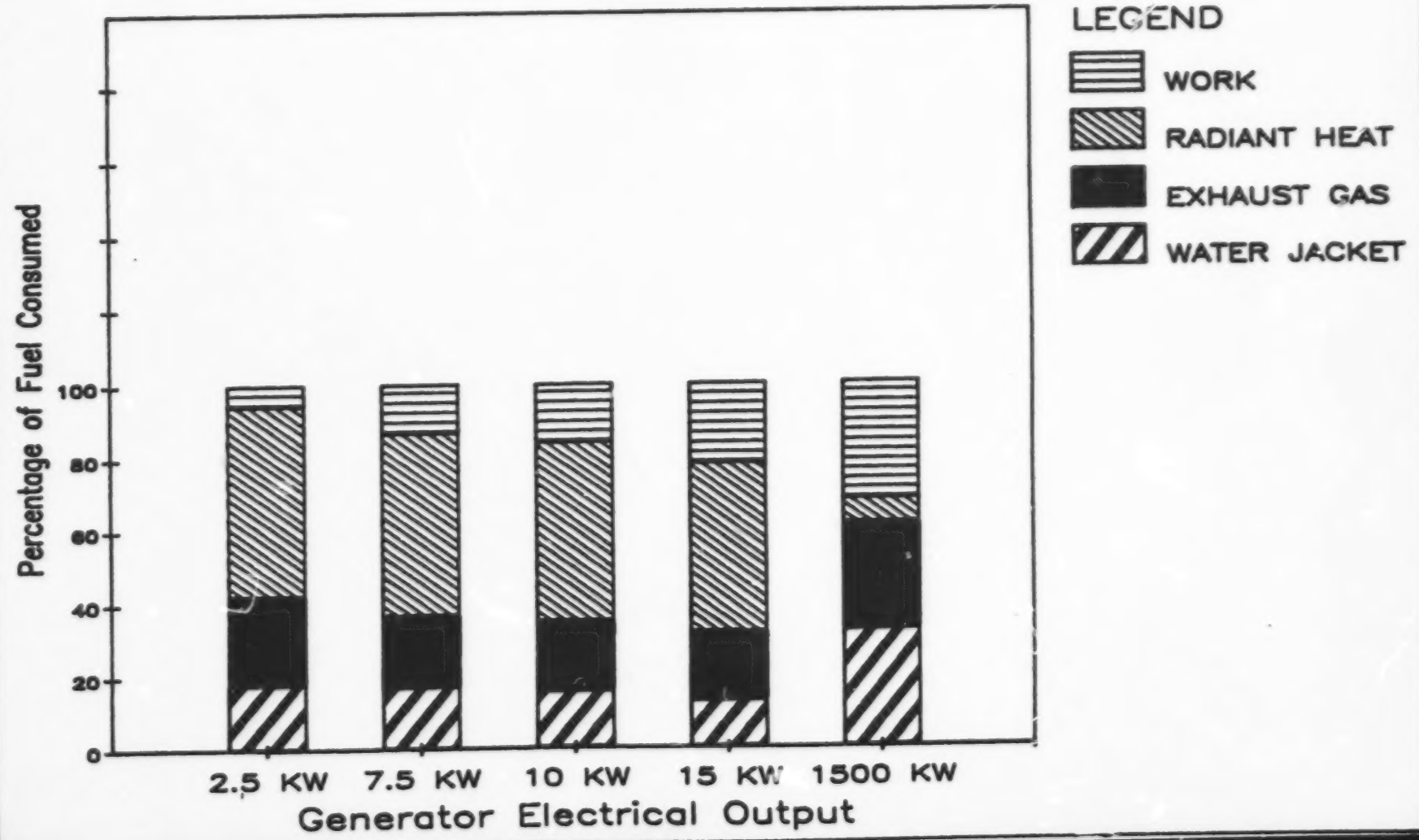
A typical heat balance for a much larger engine was provided by the engine generator set supplier (Waukesha, 1986). At an electrical output of 1500 kW, 32.4% of the fuel consumed went into the water jacket, 32.3% into work, 28.4% into the exhaust gas and 7.0% into radiant heat. The percentage of fuel consumed that is estimated to go into work is significantly higher than the percentages observed at Linden Lee Farms. The engine generator set at Linden Lee Farms is a 40 kW unit and during the trial the maximum load placed on the system was 15 kW. Operating the engine generator set at Linden Lee Farms at less than half the fuel load may have been the reason for a lower conversion into work, exhaust gas, water jacket energy, and a higher percentage of the fuel energy going into radiant heat.

4.2.1 Energy Production Potential

From the manure production and volatile solids production figures summarized in Table 4, an estimate for the energy production potential for Linden Lee Farms was calculated. In Table 4, it was estimated that 456 kg VS/d would be produced. In the previous digester monitoring study at Linden Lee Farms it was determined that the specific biogas production was 0.3 m^3/kg VS.d. Multiplying these figures would result in approximately 137 m^3 biogas/d or approximately 82 m^3 methane/d being produced. Using an energy value of 37 Mj/m^3 for methane, 3034 Mj/d would be available. From the engine performance curves, approximately 317 Mj/hr of fuel energy is required to produce 15 kW of electrical output. At a biogas production rate of 137 m^3/d, the engine generator set at Linden Lee Farms could be operated for approximately 9.5 hours/d at an electrical production rate of 15 kW. This assumes that the biogas, produced during the 14.5 hours the engine is not running, is stored.

FIGURE 3

LINDEN LEE FARMS
ELECTRICAL COGENERATION SYSTEM
ENERGY BALANCE



The active volume to store the biogas during the time the generator is shut down would be approximately 83 m^3. Table 7 summarizes a number of biogas storage options. The first low pressure storage option would provide an expandable biogas storage bag of approximately 100 m^3 total capacity. This could be accomplished with a biogas storage bag 3 m diameter x 14 m long, or 3.6 m diameter x 9.5 m long, or 4.25 m diameter x 7.25 m long. The bag would have to be appropriately housed to protect it from the elements. Storage at 35 kpa gauge pressure would require a fixed steel storage tank approximately 6 m diameter x 11 m long or 7 tanks 3 m diameter x 6.4 m long (ie. 10,000 gallon gasoline storage tanks). Increasing the biogas pressure to 135 kpa gauge pressure would require a fixed steel storage tank 3 m diameter x 8.5 m long and, at a biogas pressure of 1000 kpa gauge pressure, a fixed steel tank 1.2 m diameter x 7 m long would be required.

Table 7
BIOGAS STORAGE OPTIONS FOR LINDEN LEE FARMS

Biogas Storage Maximum Operating Pressure Kpa (psig)	Total Volume m^3	Active Volume m^3
3.5* (0.5 psig)	100	83
35 (5 psig)	320	85
135 (20 psig)	60	80
1,000 (150 psig)	8	80

* Expandable biogas storage (bag)

5.0 CONCLUSIONS

The following conclusions have been drawn from the monitoring program conducted at Linden Lee Farms:

1. When the generator output was only 2.5 kW or 6.3% of the rated capacity, the percentage of fuel energy converted to work was only 5.6%. At a generator output of 15 kW or 37.5% of the rated capacity, 21.8% of the fuel was converted to work. At low generator outputs, most of the fuel consumed goes into radiant heat and does not produce electricity and is not recovered for use in the existing recovery system.

2. It was estimated that 15 kW of electrical output could be generated for approximately 9.5 hours/day with the current barn inventory. Biogas storage would have to be installed to store the biogas that is produced while the engine generator set is not in operation. Approximately 83 m^3 of storage would be required.

3. A significant difference between the Agriculture Canada volatile solids production estimates and the actual volatile solids estimates are observed at both Linden Lee Farms and Selves Farms. The Agriculture Canada numbers over-estimate the volatile solids production from 150-184%.

4. A significant difference between the specific biogas production at Selves Farms and Linden Lee Farms was observed. This difference may be related to the ration ingredients used and the method of feeding employed in the barns. The specific gas production rate at Selves Farms was 233% of the specific gas production rate at Linden Lee Farms.

6.0 RECOMMENDATIONS

1. In order to maximize the fuel efficiency of the co-generation unit at Linden Lee Farms, the unit should be operated at as close to its maximum output as possible for as long a period of time each day as biogas is available. This will maximize the electrical power generated and the heat recovered from the unit. Operation at a low electrical output will result in poor fuel utilization and minimal heat recovery.

2. If economically feasible, biogas storage should be installed to collect all or most of the biogas produced during the generator down-time. This will allow a higher electrical production rate during the remaining hours.

7.0 REFERENCES

1. Agriculture Canada. Biogas as a Farm Energy Source. Publication I-297. 1981.

2. Canviro Consultants Ltd. "Demonstration of Energy Production and Conservation by Anaerobic Digestion and Protein Recovery at an Ontario Hog Farm. Ontario Ministry of Agriculture and Food. 1984.

3. Canviro Consultants Ltd. "Final Report on the Demonstration of Energy Production and Conservation by Anaerobic Digestion and Electrical Co-Generation of Swine Manure". Energy, Mines and Resources Canada, Conservation and Renewable Energy Demonstration Program. March 1985.

4. Waukesha Power Systems. Waukesha Cogeneration Handbook. Form No. 7030. 1986.

APPENDIX A

LINDEN LEE FARMS ELECTRICAL CO-GENERATION

SYSTEM OPERATIONAL LOG SHEET

(KIR12/12A)

APPENDIX A

LINDEN LEE FARM ELECTRICAL CO-GENERATION SYSTEM OPERATIONAL LOG SHEET

Parameter	Generator Output (kW) 2.5	7.5	10	15
Exhaust Gas/Water Heat Exchanger				
Gas Temperature In (°C)	192	231	234	225
Gas Temperature Out (°C)	43	46	46	48
Gas Flow (m^3/min)	5.10	5.35	5.83	6.08
Water Temperature In	36	37	39	41
Water Temperature Out	42	45	45	47
Water Flow	7.8	7.8	7.2	9.6
Heat Transfer	11,750	15,460	13,860	14,460
Manifold Heat Exchanger				
Water Temperature In	57	56	56	56
Water Temperature Out	71	71	71	71
Water Flow	7.8	7.8	9.2	9.6
Heat Transfer	31,330	29,370	34,640	36,150
Water/Water Heat Exchanger				
Hot Water Temperature In	68	72	71	71
Cool Water Temperature Out	36	37	39	41
Water Flow	7.8	7.8	9.2	9.6
Heat Transfer	62,660	68,530	73,910	72,300
Cool Water Temperature In (°C)	18	15	19	20
Hot Water Temperature Out (°C)	22	19	24	25
Water Flow	46.6	46.6	37.8	40.5
Heat Transfer	41,770	41,770	52,220	52,220
Digester Heating				
Water Temperature In (°C)	22	19	23	24
Water Temperature Out (°C)	17	14	17	18
Waterloo Flow (L/min)	41.6	41.6	41.6	41.6
Heat Transfer	52,220	52,220	62,660	62,660

Parameter	Generator Output (kW) 2.5	7.5	10	15
Hot Water Storage Tank				
Storage Tank Water Temperature (°C)	41	43	42	40
Waste Heat Radiator				
Water Temperature before Waste Heat Radiator (°C)	24	23	24	24
Electrical Meters				
Total Electricity Generated (kW)	2.5	7.5	10.1	15.2
Total Electricity Imported (kW)	-	-	-	-
Total Electricity Exported (kW)	NA	NA	NA	4.0
Electrical Panel				
Voltage Line 1 (volts)	235	235	235	240
Voltage Line 2 (volts)	235	235	235	240
Amperage Line 1 (amps)	25	45	50	70
Amperage Line 2 (amps)	20	40	45	65
Frequency (Hz)	59-61	59-61	59-61	59-61
Kilowattage (kW)	2.5	7.5	10	15